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Effect of changing operating policies on energy use consumption

Ahmed M. Marzouk[a], Hoda A. ElMaraghy[a,*], Waguih H. ElMaraghy[a]

[a]Intelligent Manufacturing Systems (IMS) Centre, University of Windsor, 401 Sunset Avenue, Windsor, Ontario, Canada N9B 3P4

* Corresponding author. Tel: +1 (519) 253-3000 x 5034. *E-mail address:* hae@uwindsor.ca

Abstract

Energy efficiency continues to be an important focus in manufacturing in light of energy cost, environmental concerns and legislations. Reducing energy use is essential for maintaining manufacturing sustainability and competitiveness. This paper proposes a methodology for energy use analysis that employs analytical, simulation and statistical tools for the purpose of investigating the effect of changing operating strategies such as production scheduling and batch sizes on manufacturing line total energy use. The proposed methodology identifies potential energy savings and guides improvement efforts. A real case study of an automotive OEM supplier, which experiences system changes as new products are introduced is presented. The main pieces of equipment consuming energy in the entire production line were identified and the total energy consumption per product was estimated. The manufacturing line was modelled using discrete event simulation, and the effect on the line total energy consumption of different operating strategies including different batch sizes and production schedules were determined. Analysis of Variance (ANOVA) was employed to analyze the effects of each operating strategy on the energy usage. The results reveal a relationship between changes in the operating strategies and energy use. This study demonstrated that optimizing the production line operating strategies can potentially lead to significant energy savings without the need for major modifications of equipment or machine setups. Practical examples which can guide industrial energy management practitioners in planning, assessing and improving manufacturing systems efficiently are provided. This study emphasizes the importance of including energy use data in manufacturing systems operating policy decisions.

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Keywords: Energy efficiency; Manufacturing system; Operation Policies

1. Introduction

Fierce global competition, unforeseeable market changes, reduced product life cycles and high products variety are challenges facing manufacturers now and in the future. In order to survive and maintain competitive advantage, manufacturers make changes in products, production technologies and manufacturing systems to respond to those external change drivers [1]. These drivers are commonly related to the product and its added value to the customers [2]. However, the growing awareness of energy management and related governmental legalization, is becoming a substantial concern when implementing any changes. Manufacturing activities consume significant amounts of energy which results in significant stress on the environment [3], which drives various governments in International Energy Agency (IEA) countries to implement energy efficiency enhancement policies [4]. Moreover, being an energy efficient manufacturer is not only considered a competitive advantage [5] but it also reduces overall production costs by 10-20% [6]. Accordingly, energy management continues to be an important field of research that is increasingly gaining more attention from manufacturers. Manufacturing lines energy use analysis including breaking down the plant energy consuming categories is an essential step towards achieving better energy performance [7].

Valuable information on manufacturing energy use in addition to several success stories about energy efficiency is presented by Boyd [8]. Energy use measurement is introduced as a key performance indicator (KPI) for assessing manufacturer's energy efficiency [9]. Manufactures today are required to adapt to any changes efficiently, not only economically but also in terms of energy use.

This paper investigates the possibility of achieving low cost energy saving by introducing a practical example, of a real case study of an automotive OEM supplier. The study highlights the importance of including energy use data while making

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decisions about operating policies to accomplish energy efficiency.

2. Literature Review

Pressure from governments to adopt energy efficiency in manufacturing is increasing. In 2007; EU, Asia, US, South America, and even the UN, among others, have developed and activated many regulations, penalties, tax benefits, incentives or commitments to become greener or energy efficient at different manufacturing stages [4]. Energy efficiency is increasingly becoming a mandate rather than a choice.

Research efforts in the field of energy management covers different aspects. A critical review of the state of the art of manufacturing processes energy efficiency was presented by Apostolos [10] at different levels (process, machine, line and plant). At machine level, energy management focuses on enhancing energy efficiency by optimally selecting cutting conditions [11]. Monitoring approaches for energy consumption of machine tools [12], and accordingly obtaining energy performance KPIs in real time [13] was reported. Value stream mapping was used to analyze the value-added vs. non-value added energy use in machining cycles [14].

On the operational level, a study by Skoogh [15] shows that considerable amounts of energy are wasted in non-value added activities such as equipment idle states and other non-machining activities. This can be attributed to underutilization of machines, unplanned maintenance activities and scheduling problems. It was shown that there are significant opportunities for energy saving through better management of the equipment without major technological or setup modifications.

The focus of this paper is to provide a practical energy use analysis methodology to investigate the effect of changing operating policies on energy use consumption of the manufacturing line.

3. Assessing the effect of changing operating policies on energy consumption

A methodology has been developed to identify achievable energy saving opportunities within a manufacturing line without the need for major modification in machine technologies, based on varying operating policies. The proposed methodology is composed of six steps as illustrated in Figure 1. It integrates system simulation tools, such as discrete event simulation with statistical tools such as Analysis of Variance (ANOVA).

3.1 Production flow and energy consumption analysis using discrete event simulation

Computer-based simulation models were recently used, as a powerful tool in monitoring and predicting energy consumption. Simulation models can be classified into continuous and discrete categories. The advantages and disadvantages of using each of them are discussed in Bouchhima [16]. For the analysis of the material flow, the discrete event simulation (DES) is more advantageous in analyzing the dynamics of a production system [17]. A practical example of developing simulation models for energy use where system energy use performance is monitored can be found in Skoogh [18]. Bleicher [19] introduced the Co-simulation approach, where the manufacturing system performance model and the energy use model are synchronized into one overall model. Kohl [20] illustrated the potential of predicting energy consumption of individual products and their variants using discrete event simulation.

3.2 Machines energy use data collection

Energy use data collection precision is an important prerequisite in energy management. Energy use data is normally generated by energy measurement devices, such as energy meters, in the form of extensive readings of average power consumption per unit time (e.g. seconds) over a planned time period.

Information about states of the measured equipment is needed for accurate interpretation of the collected energy data during the same period [21]. This information can be gathered during data collection. Processing, idle, warming-up and standby are just some examples of possible machine states during manufacturing. The processing state is associated with a product being manufactured on the machine. The idle state means that all machine components are turned on waiting for a product from a preceding machine on the line, while a standby state means that machine controllers have to remain on overnight when all other components are turned off to preserve the controller programs. The warm-up state for some machines, is obligatory every time the machine is turned on to warm-up machine components. The energy measurement process showed that different machines do not share the same operating states.

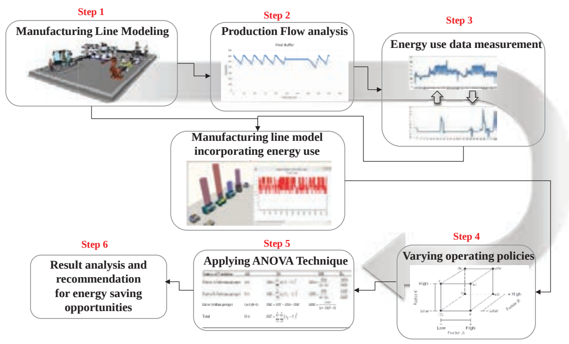

Fig. 1. Steps for identifying energy saving opportunities based on changing operating policies

3.3 Design of Experiments

Observing a system while it is in operation is an important part of learning about how systems and processes work. An experiment is a test or series of runs in which purposeful changes are made to the input variables of a system so that we may observe and identify the reasons for changes in the observed output response [22]. Factorial design is an experimental tool where complete trial or experiment replicate of all possible combinations of factor levels are investigated. The effect of a factor is defined as the change in response produced by a change in the level of the factor. This is frequently called a main effect because it refers to the primary factors of interest in the experiment. Analysis of variance (ANOVA) is a statistical model which is widely used to interpret experimental data, and for detecting differences in average performance of groups of items tested. It divides total variation into accountable factors. The main objective of ANOVA is to extract from the experimental results how much of a variation each factor causes relative to the total variation observed in the result [23]. The use of DOE modeling for energy use in the automotive industry, which measures the expected energy use performance of the different system components based on their corresponding characteristics as well as dynamic operational states, showed successful results [24].

3.4 Energy Modelling and Analysis Methodology

The first step is creating a discrete event simulation model of the manufacturing line. The second step is using the model in production flow analysis such as finding needed operating hours to achieve desired production volume and buffer capacities. Validation of the simulation model is done before integrating the energy data into the simulation model. The third step is gathering energy use data for individual pieces of equipment in the line and identifying their states followed by integrating energy data with the simulation model. This integrated simulation model, incorporating energy data, calculates total energy use of the manufacturing line as well as energy consumed per manufactured product. The fourth step is using the integrated model to analyze energy use consumption while varying different operating policy factors such as operating hours, production schedule and batch sizes. The fifth and sixth steps use the ANOVA technique to interpret and analyze the experiment's outcomes.

4. Case study

The developed methodology was applied on a real case study of a job shop automotive OEM supplier adapted from Fredriksson et al. [25]. The company supplies automotive instrument panels to its main customer. This customer plans to introduce a new product to the market aiming to achieve 170,000 sales per year. The OEM customer facility operates 16 hours per day divided over two shifts and 251 working days per year. The products are delivered bi-hourly to its assembly line. Vehicle instrument panels will be produced in two main product variants. The line consists of four main departments as shown in Figure 2.

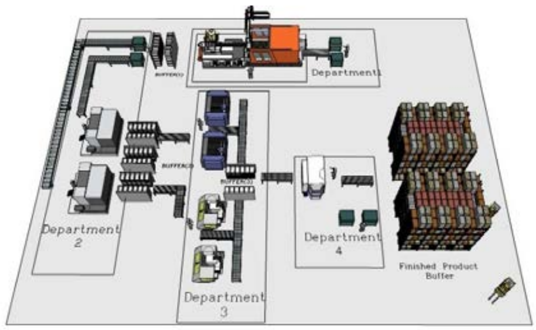

Fig. 2. Job shop floor layout

Production flow starts with Department 1, which is a common stage for all panel variants. It includes a preparation stage and an injection molding machine. Switching between variants requires machine setup for tool changing. The next stage is Department 2 which consists of a skin preparation station and two foaming machines, each of which is dedicated to one of the panel variants.

After the foaming process, all products go into a buffer. Products must wait in the buffer for at least 45 minutes before they can be further processed for technical consideration. The next stage is Department 3, where products are processed either on Cutting 1 or Cutting 2 machines according to their type with no tool change requirement. The last stage before the final buffer is Department 4, which consists of two stations; a welding machine and one dedicated to quality control.

Machines cycle times are listed in Table 1. The buffers between various production stages such as buffer 1, 2, and 3 are needed to deal with the unbalance between different departments. Products are processed in batches, however, the production sequence will be decided at Department 1, according to customer orders. Accordingly, switching between different panel variants will result in machine setups and tool changes in the affected machines.

Table1. Machines cycle time

Department	**Machine/Station**	**Cycle time (sec.)**
Department 1	Preparation	89
	Injection Molding	106
Department 2	Skin Preparation	45
	Foaming M/C 1	120
	Foaming M/C 2	106
Department 3	Cutting M/C 1A	288
	Cutting M/C 1B	288
	Cutting M/C 2A	204
	Cutting M/C 2B	204
Department 4	Welding M/C	89
	Quality Control	122

5. Results

5.1 Production flow analysis

Discrete event simulation model of the job shop floor was created and used for production flow analysis. Determining the required operating time needed for each machine is based on achieving the desired production volume as well as minimizing unneeded products in buffers between different departments.

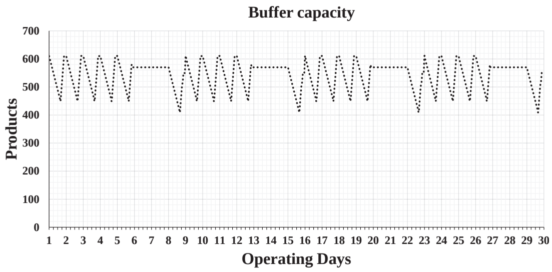

Fig. 3. Finished product buffer behavior

Figure 3 shows the accumulated products in the finished product buffer at the end of the production line; starting with almost a day worth of production as safety stock. The buffer size becomes stable after running for 30 days. The different weekly operating times needed for each department is shown in Table 2. These operating times result in a buffer capacity of 600 products with a safety allowance of 10 % (Figure 3). Table 3 illustrates the distribution of operating hours over normal production days assuming five days per week and three shifts each day. It can be seen that Department 1 and Department 4 are almost working three shifts while two shifts are sufficient for Department 2. Department 3 works two hours short in the second shift.

Table 2. Number of operating hours needed for each department per week

Department	Weekly needed operating time (hrs)
Department 1	104
Department 2	80
Department 3	70
Department 4	120

Table 3. Daily production schedule for each department

Days	Shifts	Department 1	Department 2	Department 3	Department 4
Monday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am	4:00 pm - 10:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am			12:00 am - 5:30 am
Tuesday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am	4:00 pm - 10:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am			12:00 am - 5:30 am
Wednesday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am	4:00 pm - 10:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am			12:00 am - 5:30 am
Thursday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am	4:00 pm - 10:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am			12:00 am - 5:30 am
Friday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am	4:00 pm - 10:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am			12:00 am - 5:30 am

5.2 Energy data gathering and measurements

The used energy measurement device, PowerVisa by Dranetz, provided a second by second average power consumption. The device was connected to the incoming 3-phase wires for each machine. The machine states were captured using a clock synchronized with the PowerVisa device's clock

Average energy consumption for each department can be found in Table 4. Subdividing the daily energy consumed by each department shows that for Department 1 almost 7 % of the total daily energy consumption (Kwh) is consumed during the warm-up period due to the presence of an injection molding machine, while the setup consumed only 1 % and the rest of the energy was consumed in product processing. In Department 2, the main contribution of energy consumption is from the processing state and standby state which are about 0.4 % of the total energy consumed. Departments 3 and 4 showed a similar pattern of consumption to Department 2.

Table 4. Average daily energy consumption for different departments

Department	Average daily energy consumption (Kwh)
Department 1	4179
Department 2	1181
Department 3	1862
Department 4	313

5.3 Experiments results of changing operating policies and their effect on energy consumption

This section investigates the effect of changing operating policies on energy use consumption of this manufacturing line. The experiment was done by varying three chosen parameters and examining one main response which is energy consumed per product (Kwh/product). The three parameters representing manufacturing line operating policies are: production schedule, machine operating hours, and batch size. As seen in Table 5 the Department 1 production schedule for Scenario 1 is divided into three shifts throughout a 5 day week. Whereas in Scenario 2 the production schedule is modified by redistributing the hours, condensing shifts, and ultimately eliminating two shifts making it appear to be an ideal alternative.

Table 5. Two different scenarios for operating department 1

Days	Shift	Operating Scenario #1	Operating Scenario #2
Monday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am	12:00 am - 8:00 am
Tuesday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am	12:00 am - 8:00 am
Wednesday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am	12:00 am - 8:00 am
Thursday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am	
Friday	Shift 1	8:00 am - 4:00 pm	8:00 am - 4:00 pm
	Shift 2	4:00 pm - 12:00 am	4:00 pm - 12:00 am
	Shift 3	12:00 am - 3:30 am	

The second parameter to be varied is the operating hours of Department 2, which can run from 14 hours to 16 hours every day in order to produce sufficient safety stock. The last parameter varies batch sizes between normal batch sizes (B1) and doubling the batch size (B2) to investigate the effect of reducing the number of setups on energy consumption. The main difference between Parameters 1 and 2 is that in Parameter 1 the needed work hours are distributed differently, while Parameter 2 represents a decision to operate for more than the needed hours in order to secure an inventory buffer.

Table 6. Experiment parameters and their corresponding levels

	Experiment parameters	Level 1	Level 2
1	Production schedule for department 1	Scenario #1	Scenario #2
2	Operating hours for department 2	14 hrs/day	16 hrs/day
3	Batch size	B1	B2 (2*B1)

Using the abovementioned parameters and their levels (Table 6), 2^3 factorial design with 8 experiments were performed. Table 7 shows the different experiment combinations and their resulting response data named Energy (Kwh) per product. Using Minitab 17 statistical package, Analysis of variance (ANOVA) was used to determine the significant effect of each factor. The ANOVA table can be seen in Table 8. The analysis was carried out for a significance level of $\alpha = 0.05$ (confidence interval of 95%). If the F value of a factor exceeds F0.05, it means that this factor has a significant effect on the main response which is energy consumption.

According to ANOVA table, operating hours for Department 2 and production schedule for Department 1 have significant effect on consumed energy (Kwh) per product, while changing batch sizes does not have a significant effect on energy consumed per product. A Main Effect Plot (Figure 4) is used for gaining better understanding of ANOVA results. The Main Effect Plot is a graphical demonstration of the mean value of different groups of data.

Table 7. Experiments result

Batch size	Operating hours	Production schedule	Energy (Kwh) per product
B1	14	Scenario #1	10.11
B2	14	Scenario #2	9.95
B2	14	Scenario #1	10.14
B1	14	Scenario #2	9.99
B2	16	Scenario #2	10.26
B1	16	Scenario #1	10.30
B1	16	Scenario #2	10.27
B2	16	Scenario #1	10.33

Table 8. ANOVA table

Parameters	DF	Adj SS	Adj MS	F-Value	P-Value
Batch	1	0.000013	0.000013	0.01	0.938
Department 2 operating hours	1	0.117613	0.117613	64.89	0.001
Department 1 production schedule	1	0.021013	0.021013	11.59	0.027
Error	4	0.00725	0.001813		
Total	7	0.145888			

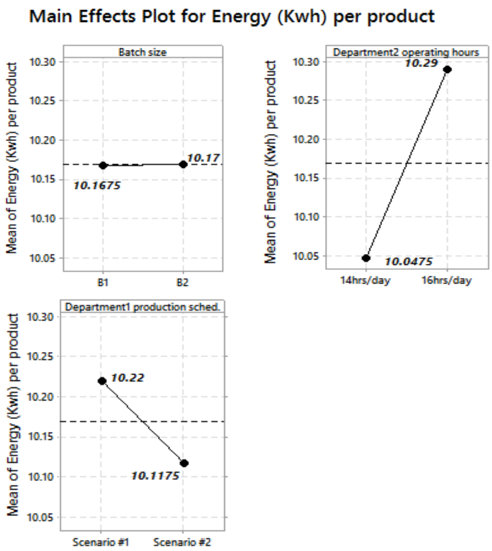

Fig. 4. Main Effect Plot of energy (Kwh) consumption per product

The Main Effect Plot (Figure 4) represents the mean reading of energy (Kwh) per product at the various levels of each parameter (refer to Table 6 for parameters and their corresponding levels). The dotted reference line on each plot represents the mean of the experiment response data named energy (Kwh) per product. The straight line connects the means of a single factor level to show the trend but it does not represent a linear relationship between the two levels.

The outcome from the Main Effect Plot (Figure 4) supports the result shown in the ANOVA table. It can be seen that increasing Department 2 operating hours leads to significant increase in energy consumed per product (0.2425 Kwh) due to the fact that the machines consume more energy during the processing state. Comparing the two scenarios for Department 1 reveals that Scenario 2 (condensed shifts) consumes less energy per product than Scenario 1 (ordinary shifts) by about 0.1025 Kwh per product. A thorough investigation shows that Scenario 2 decreases the number of warm-ups by allowing the machines to work for the first four days continuously compared to Scenario 1 which requires a shutdown of the machines every day and starting again for the next production day. Consequently, some energy savings are achieved by decreasing the number of warm-up times for the injection molding machines. The effect of changing the batch size on energy consumed per product was found to be fairly small because the energy consumed during setup is relatively small compared with the energy consumed during the processing state as indicated in section 5.2.

Table 9. Main parameters and interaction effects

Parameters	Effect
Batch size	0.0025
Department2 operating hours	0.2425
Department1 production schedule	-0.1025
Batch size * Operating hours	0.0075
Batch size * Schedule	-0.0275
Operating hours * Schedule	0.0525
Batch size * Operating Hours * Schedule	0.0075

More extensive data about the main and interaction effects of the three parameters (production schedule, operating hours and batch size) on energy consumption are presented in Table 9. Clearly, many of the calculated interaction effects appear to be sufficiently insignificant. The results from this case study are case specific and depend on the line characteristics, the type of machines and their working conditions and energy use consumption related to the various states such as warm-up or setup. The results present a practical illustration of ways to achieve energy savings by better management of resources without making hardware changes or capital investments.

6. Summary and conclusions

A methodology for assessing the effect of changing operating policies on energy consumption was proposed. It considers the existing reality (i.e. machines' technology and setup) as a default, aiming to provide energy management teams in industries with solutions to achieve low-cost improvement potentials in energy consumption. The developed approach was applied to a real case study; a job shop supplier to an automotive OEM. The results highlight a relationship between changing operating policies and energy use consumption. Integrating discrete event simulation models and energy analysis proved useful and can be applied to different case studies. This study demonstrates the presence of low cost energy saving opportunities that can be easily achieved through better management of the equipment without major technological or setup modifications. The proposed methodology provides energy management practitioners with a practical tool for assessing the status of energy use efficiency and setting achievable reduction targets in manufacturing lines without major investments. Future work includes other types of equipment such as transporters and investigating more operating policies.

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